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DETECTION OF DUST IN DAMPED LYMAN-ALPHA SYSTEMS

S. MICHAEL FALL AND YICHUAN C. PEI
Space Telescope Science Institute; and Department of Physics and Astronomy, The Johns Hopkins University
AND
RICHARD G. MCMAHON
Institute of Astronomy, University of Cambridge
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ABSTRACT

We find that quasars with damped Lyα systems in the foreground tend to appear redder than those without damped Lyα systems in the foreground. Our detection, at or above the 99% confidence level, is based on the spectra recently obtained by Sargent, Steidel, and Boksenberg. We estimate that the typical dust-to-gas ratio in the damped Lyα systems is 1/20 to one-fourth of that in the Milky Way, with the exact value depending on the shape of the extinction curve. A comparison of our results with the upper limits from previous searches suggests that the 2200 Å feature may be weak or absent. This and the small dust-to-gas ratio are consistent with other evidence that the damped Lyα systems are in an early phase of chemical evolution. The dust we have detected is probably sufficient to extinguish a large fraction of any Lyα photons emitted within the damped Lyα systems.

Subject headings: cosmology — galaxies: intergalactic medium — quasars

I. INTRODUCTION

The damped Lyα systems discovered in the spectra of distant quasars are natural places to search for dust. They have column densities of neutral hydrogen in excess of 10^{20} cm^{-2} and may be the progenitors of present-day galactic disks. In a pioneering study, Wolfe *et al.* (1986, hereafter WTSC) found that the total mass of neutral hydrogen in the damped Lyα systems is comparable to that in all forms of luminous matter at the present epoch. Any dust in the damped Lyα systems would cause the quasars behind them to appear redder than quasars without damped Lyα systems along the lines of sight. From the absence of such an effect in the WTSC survey, Fall and Pei (1989, hereafter FP) concluded that the dust-to-gas ratio in the damped Lyα systems is less than half the observed value in the Milky Way. FP also showed that the contribution by damped Lyα systems to the mean optical depth in the B band along random lines of sight to a redshift of 3 is less than unity.

In this *Letter*, we analyze a new sample—that of Sargent, Steidel, and Boksenberg (1989, hereafter SSB). Their primary goal was to obtain homogeneous data on Lyman-limit systems, but they also presented results on the damped Lyα systems that were found. The SSB spectra satisfy the two conditions identified by FP as being necessary for improved limits or a detection of dust in the damped Lyα systems: (1) The coverage in wavelength should be large enough that the spectral indices can be determined redward of the Lyα forest; and (2) the observational errors in the spectral indices should be comparable to or smaller than the intrinsic dispersion between quasars. With these improvements over the WTSC spectra, we can now make a more sensitive test for reddening in the damped Lyα systems. The detection reported here has a bearing on the nature of the damped Lyα systems and possibly on searches for primeval galaxies. In a subsequent paper, we present new estimates of the mean optical depth along random lines of sight.

II. THE SSB SAMPLE

The SSB sample consists of 59 quasars with $z_e > 2.75$ from the catalogs by Hewitt and Burbidge (1987), Véron-Cetty and Véron (1987), and Hazard and McMahon (1989).[1] Of these, 45 were originally discovered in optical surveys, and the remaining 14 were discovered in radio surveys. Most of the quasars are brighter than $V \approx 18.5$, but some of them are as faint as $V \approx 19.5$. While the SSB sample is heterogeneous in these respects, it should be unbiased with regard to absorption features and therefore suitable for our analysis. All quasars were observed with the double spectrograph on the 5 m Hale telescope at resolutions of 4–6 Å over the range of wavelengths 3150 Å $\leq \lambda_o \leq$ 7000 Å. In a few cases, the spectra were corrected for Galactic reddening. SSB determined the spectral indices α_o redward of Lyα emission by continuum fits of the form $\log f_o(\nu) = -\alpha_o \log \nu + \text{const}$. The errors in α_o are estimated to be ± 0.1. The mean spectral index is 0.78, and the standard deviation about the mean is 0.27.

SSB identified 15 strong absorption features as candidate damped Lyα lines. After Voigt-profile fitting, six of these appeared to be blends of weaker, probably undamped lines, and one was not strong enough for the H I column density to be estimated. The remaining eight features, which are almost certainly damped Lyα lines, have 3×10^{20} cm^{-2} $\leq N_{\rm H\,I} \leq 3 \times 10^{21}$ cm^{-2} and $2.14 \leq z_a \leq 3.39$. We refer to the seven spectra with these lines as the "damped subsample" and the other 44 spectra without broad absorption lines (BALs) as the "control subsample." According to SSB, the identification of damped Lyα lines is complete only for $N_{\rm H\,I} \gtrsim 1 \times 10^{21}$ cm^{-2}. This should not bias our estimates of the dust-to-gas ratio because unidentified damped Lyα lines with smaller column densities will be present with nearly equal probability in the

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[1] Throughout this *Letter*, the subscript e refers to emission, a to absorption, and o to observation. Only one quasar in the SSB sample was discovered on the basis of its optical colors.

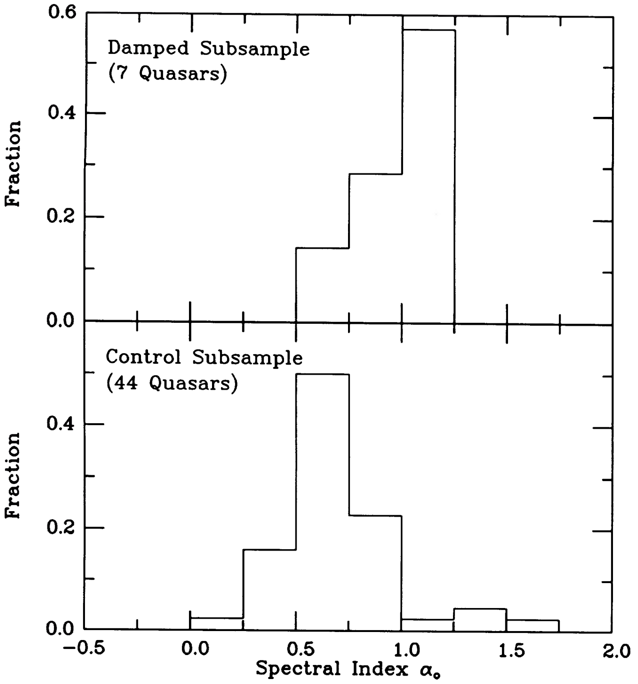

FIG. 1.—Histograms of the observed spectral indices in the damped and control subsamples. The former are stochastically redder than the latter.

control and damped subsamples. We have checked that the distributions of emission redshifts and apparent magnitudes of the quasars in the two subsamples are statistically indistinguishable. Moreover, the fraction of radio-loud quasars in the damped subsample (two out of seven) is nearly identical to that in the control subsample (12 out of 44).

III. THE DUST-TO-GAS RATIO

Figure 1 shows histograms of the observed spectral indices in the damped and control subsamples. Evidently, the spectra with damped Lyα are stochastically redder than those without damped Lyα, a result confirmed at the 99.7% confidence level by a Mann-Whitney U-test. We assume that the reddening is caused by dust and estimate its abundance following the methods of FP. Our results are expressed in terms of the dimensionless "dust-to-gas ratio" $k \equiv 10^{21}(\tau_B/N_{\rm H\,I})$ cm^{-2}, where τ_B is the optical depth in the B band in the rest frame of an absorber. For each quasar with damped Lyα along the line of sight, the difference between the indices of the observed and emitted spectra, $\Delta\alpha \equiv \alpha_o^d - \alpha_e^d$, is a known function of k (see eq. [1] below). Since the SSB sample is unbiased with regard to absorption features, we can assume that the indices of the emitted spectra in the damped and control subsamples, α_e^d and α_e^c, were drawn at random from the same parent population. Our goal is therefore to find values of k such that the distribution of $\alpha_o^d - \Delta\alpha$ is statistically indistinguishable from the distribution of α_o^c.

We assume for the moment that the dust-to-gas ratio is the same in all the damped Lyα systems. The reddening of a quasar is then

$$\Delta\alpha = -k \sum_a \left(\frac{N_{\rm H\,I\,a}}{10^{21}\ {\rm cm}^{-2}}\right) \frac{d\xi(\lambda_a)}{d\ln\lambda_a}, \qquad (1)$$

where $\xi(\lambda_a) \equiv A(\lambda_a)/A(4400\ \text{Å})$ is the ratio of the extinction at the absorption wavelength $\lambda_a = \lambda_o/(1+z_a)$ to that in the B band, and the sum is over all damped Lyα systems along the line of sight. To allow for a wide range of conditions within the damped Lyα systems, we use the mean extinction curves from the Milky Way and the Large and Small Magellanic Clouds (LMC and SMC; see Fig. 1 of FP). The derivatives $d\xi(\lambda_a)/d\ln\lambda_a$ are evaluated over the range of wavelengths 1216 Å $\leq (1+z_a)\lambda_a/(1+z_e) \leq$ 1549 Å, i.e., between Lyα and C IV emission when blueshifted into the rest frame of each absorber. This corresponds roughly to the range of wavelengths over which the spectral indices were fitted.

We estimate the dust-to-gas ratio in the damped Lyα systems using a Mann-Whitney U-test. The advantage of this or any other nonparametric test is that it does not require a specific model for the distribution of spectral indices. In our problem, the statistic U, the number of times a value of $\alpha_o^d - \Delta\alpha$ exceeds a value of α_o^c in the combined sample, is a function of k. We obtain $P(<k)$, the probability that the dust-to-gas ratio is less than k, from $U(k)$ and the sampling distribution of U under the null hypothesis that $\alpha_o^d - \Delta\alpha$ and α_o^c were drawn at random from the same parent population. Since the damped subsample is relatively small, we compute probabilities from the exact recursion relation given by Mann and Whitney (1947) rather than the asymptotic normal distribution. We also set $P(<k) = 0$ for $k < 0$, because negative dust-to-gas ratios are unphysical, and enforce the normalization $P(<k) \to 1$ for $k \to \infty$. Finally, we smooth over the many small jumps in $P(<k)$ so that the probability density $p(k) \equiv dP(<k)/dk$ can be approximated by a continuous function.

The upper panel of Figure 2 shows the cumulative probabilities derived with the three different extinction curves. Setting $P(<k) = 0.95$, we obtain the following upper limits on the dust-to-gas ratio in the damped Lyα systems:

$$k \leq 0.38\ ({\rm GAL})\,, \quad k \leq 0.10\ ({\rm LMC})\,, \quad k \leq 0.06\ ({\rm SMC})\,. \qquad (2)$$

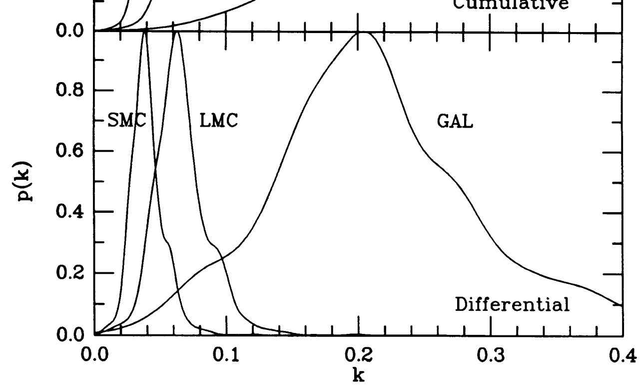

FIG. 2.—Cumulative and differential probabilities derived from the U-tests for the Galactic, LMC, and SMC extinction curves. The most probable values of the dust-to-gas ratio k_p occur at the peaks of $p(k)$.

These are smaller than the corresponding results derived by FP from the WTSC survey by factors up to 3. The large variation in the new limits is a consequence of the different strengths of the 2200 Å feature in the adopted extinction curves and the longer wavelengths at which the spectral indices were fitted. In the present study, the derivatives $d\xi(\lambda_a)/d\ln\lambda_a$ that appear in equation (1) were evaluated over the range $1200\ \text{Å} \lesssim \lambda_a \lesssim 1900$ Å. The Galactic extinction curve is flat at the end of this range because the 2200 Å feature is strong, whereas the LMC and SMC extinction curves are relatively steep because the 2200 Å feature is weak or absent.

The differential probabilities $p(k)$ are shown in the lower panel of Figure 2. These have well-defined peaks at the most probable values of the dust-to-gas ratio. We find, for the three different extinction curves,

$$k_p = 0.20 \pm 0.07\ (\text{GAL})\,, \quad k_p = 0.06 \pm 0.02\ (\text{LMC})\,,$$
$$k_p = 0.04 \pm 0.01\ (\text{SMC})\,. \qquad (3)$$

The one sigma errors were computed from the usual relation $P(<k_p + \epsilon_p) - P(<k_p - \epsilon_p) = 0.68$. Evidently, the most probable values of the dust-to-gas ratio in the damped Lyα systems differ from zero at about the three sigma level. We again find the largest results for the Galactic extinction curve because it has the strongest 2200 Å feature. For comparison, the observed dust-to-gas ratios in the Milky Way and the Large and Small Magellanic Clouds are, respectively, $k = 0.79$, $k = 0.19$, and $k = 0.05$ (FP and references therein).

We have repeated the analysis described above with various modifications of the basic damped and control subsamples. Excluding the two spectra with $N_{\rm H\,I} < 1 \times 10^{21}$ cm^{-2} from the damped subsample gives $k_p = 0.19 \pm 0.07$ (GAL), $k_p = 0.06 \pm 0.02$ (LMC), and $k_p = 0.04 \pm 0.01$ (SMC). When the spectrum of Q0000−263, which has the least certain index, is excluded from the damped subsample, we find $k_p = 0.19 \pm 0.07$ (GAL), $k_p = 0.06 \pm 0.02$ (LMC), and $k_p = 0.04 \pm 0.01$ (SMC). Including the BAL spectra in the control subsample gives $k_p = 0.17 \pm 0.07$ (GAL), $k_p = 0.06 \pm 0.02$ (LMC), and $k_p = 0.04 \pm 0.01$ (SMC). When the spectra of radio-loud quasars are excluded from both the damped and control subsamples, we find $k_p = 0.22 \pm 0.08$ (GAL), $k_p = 0.07 \pm 0.02$ (LMC), and $k_p = 0.04 \pm 0.01$ (SMC). In all these tests, the spectra with damped Lyα are stochastically redder than the spectra without damped Lyα at or above the 99% confidence level. We conclude that our results are not sensitive to the exact way in which the subsamples are defined.

Our assumption that the dust-to-gas ratio is the same in all the damped Lyα systems was made for simplicity. To check whether this has affected our estimates, we have also performed a series of Monte Carlo calculations in which the logarithms of the individual dust-to-gas ratios k_a were drawn at random from a Gaussian distribution. The lognormal distribution has the desirable property that negative values of k_a are automatically excluded. Using the methods described above, we have determined the most probable value of the mean $\langle \ln k \rangle_p$ as a function of the assumed dispersion $\sigma(\ln k)$. We find that $\langle \ln k \rangle_p$ decreases monotonically with $\sigma(\ln k)$ but does not differ from the results derived with a constant dust-to-gas ratio by more than the one sigma errors for $\sigma(\ln k) \leq 1.2$. Thus, the most probable values given in equation (3) can be interpreted as the "typical" dust-to-gas ratios in damped Lyα systems with 3×10^{20} cm$^{-2} \lesssim N_{\rm H\,I} \lesssim 3 \times 10^{21}$ cm^{-2}.

TABLE 1

UPPER LIMITS ON GALACTIC-TYPE DUST IN DAMPED LYMAN-ALPHA SYSTEMS

Quasar	z_a	$N_{\rm H\,I}/10^{21}$ cm^{-2}	Reference	$k_{\rm max}$	Reference
PHL 957	2.31	2.5	1	0.12	6
PKS 0528−250	2.81	1.3	2	0.61	7
PKS 1157+014	1.94	6.3	3	0.08	3
MC 1331+170	1.78	1.5	4	0.08	6
Q1337+113	2.80	0.8	5	0.39	5

REFERENCES.—(1) Black, Chaffee, and Foltz 1987; (2) Foltz, Chaffee, and Black 1988; (3) Wolfe, Briggs, and Jauncey 1981; (4) Chaffee, Black, and Foltz 1988; (5) Lanzetta, Wolfe, and Turnshek 1989; (6) Jura 1977; (7) Smith, Jura, and Margon 1979.

IV. DISCUSSION

Most previous searches for dust in damped Lyα systems were attempts to find broad absorption features produced by a bump in the extinction curve at $\lambda_a \approx 2200$ Å. We summarize the null results of these studies in Table 1, scaled in several cases to more recent determinations of the H I column densities. All five upper limits are based on the Galactic extinction curve. The fact that three of them are smaller than the most probable value of the dust-to-gas ratio we have derived with the Galactic extinction curve is a tentative indication that the 2200 Å feature is weaker in the damped Lyα systems than in the Milky Way.[2] This might be explained by a lower abundance of graphite in the damped Lyα systems. In any case, our detection is entirely consistent with previous searches if the shape of the extinction curve is similar to that in the LMC or SMC and the dust-to-gas ratio is roughly 10% of that in the Milky Way.

What are the damped Lyα systems? They appear to have low abundances of heavy elements but the uncertainties are large, with $10^{-2} \lesssim Z/Z_\odot \lesssim 1$ allowed, because most of the gas is in a "quiescent" component ($\sigma \lesssim 10$ km s^{-1}) while the equivalent widths of the metal lines are determined mainly by the velocity dispersion ($\sigma \gtrsim 20$ km s^{-1}) in a "turbulent" component (Turnshek *et al.* 1989). Moreover, several recent studies indicate that the abundances of molecules are well below those in the Milky Way (Chaffee, Black, and Foltz 1988 and references therein; Lanzetta, Wolfe, and Turnshek 1989). The evidence presented here for a small dust-to-gas ratio and a weak 2200 Å feature also suggests that the damped Lyα systems are in an early phase of chemical evolution. In this respect, they resemble nearby gas-rich dwarf galaxies and, hypothetically, the progenitors of present-day galactic disks. The latter possibility is favored by the large fraction of the sky covered by the damped Lyα systems, but a highly inflated population of dwarf galaxies cannot be ruled out.

The dust we have detected may account for the absence of strong Lyα emission in the observed spectra of several damped Lyα systems (Foltz, Chaffee, and Weymann 1986). According to Adams (1975), resonance-line photons are "thermalized" when the optical depth in the continuum τ_d satisfies the relation $\tau_d(a\tau_0)^{1/3} \gtrsim 1$, where a is the damping constant and $\tau_0 > 10^6$ is the optical depth at the center of the line. This defines a

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[2] For the two weakest limits in Table 1 (largest $k_{\rm max}$), the 2200 Å feature would appear at $\lambda_o \approx 8400$ Å, where the spectrophotometry is least reliable. The absorption system toward PKS 0215+015 studied by Boissé and Bergeron (1988) has not been included because there is no evidence that it is damped (Blades *et al.* 1985).

critical column density, which for hydrogen, is

$$N_{\rm H\,Icrit} \simeq 1.3 \times 10^{20}(k/0.1)^{-3/4}(\sigma/10\ {\rm km\ s^{-1}})^{1/2}\ {\rm cm^{-2}}\ . \quad (4)$$

With our estimates of k and typical values of σ, most damped Lyα systems have $N_{\rm H\,Icrit} \lesssim N_{\rm H\,I}$. We therefore expect a large fraction of any Lyα photons produced within them to be extinguished by the dust. (The exact attenuation depends on whether the emission occurs near or far from the surface and how the gas and dust are mixed.) We suggest that the rates of star formation in the damped Lyα systems could be much higher than any limits derived without dust. Moreover, most damped Lyα systems would probably not be detected in "blank-sky" searches for Lyα emission from primeval galaxies.

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S. MICHAEL FALL and YICHUAN C. PEI: Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

RICHARD G. McMAHON: Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England